

Massive Binary WR112 and Properties of Wolf-Rayet Dust

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ABSTRACT

Some hot, massive, population-I Wolf-Rayet (WR) stars of the carbon subclass are known to be prolific dust-producers. How dust can form in such a hostile environment remains a mystery. Here we report the discovery of a relatively cool, extended, multi-arc dust envelope around the star WR112, most likely formed by wind-wind collision in a long-period binary system. We derive the binary orbital parameters, the dust temperature and the dust mass distributions in the envelope. We find that amorphous carbon is a main constituent of the dust, in agreement with earlier estimates and theoretical predictions. However, the characteristic size of the dust grains is estimated to be $\sim 1\mu m$, significantly larger than theoretical limits. The dust production rate is $6.1 \times 10^{-7} M_{\odot} \text{yr}^{-1}$ and the total detectable dust mass is found to be about $2.8 \times 10^{-5} M_{\odot}$ (for $d = 4.15$ kpc). We also show that, despite the hostile environment, at least $\sim 20\%$ of the initially-formed dust may reach the interstellar medium.

Subject headings: infrared: stars — stars: Wolf-Rayet — stars: winds, outflows

1. Introduction

Classes of objects known to produce significant quantities of dust include asymptotic giant-branch stars, red giants, novae, supernovae (each of which contributes about equal rates, $\sim 10^{-3} M_{\odot} \text{yr}^{-1}$, of dust in the whole Galaxy), along with planetary nebulae and proto-stars (each of which yields ~ 10 times less; Dwek 1985). Surprisingly, some hot, massive, population I WR stars also form dust (van der Hucht, Williams, & Thé et al. 1987). WR stars are the evolved descendants of massive O-type stars. They consist mainly of He-burning cores surrounded by hot envelopes that drive fast, dense winds with average mass-

loss rates $\sim 10^{-5} M_{\odot} \text{yr}^{-1}$ and terminal velocities $v_{\infty} \sim 1000 - 4000 \text{ km s}^{-1}$. There are three successive WR phases, WN, WC and WO, characterized by the dominant emission lines of N, C, and O, respectively, in their optical spectra. All dust-making WR stars belong to the carbon-rich, hydrogen-poor WC subclass (Williams 1995). The WR dust-makers are remarkable for two main reasons: (1) the absolute rate of formation is very high, up to $10^{-6} M_{\odot} \text{yr}^{-1}$ in dust alone, and occurring in either a periodic (due to enhanced wind-wind compression at or near periastron passage in long-period WC + O binaries with eccentric orbits) or sustained fashion (in single late-type WC stars or moderately short-period WC + O binaries with circular orbits); and (2) the dust is formed in a hot, extremely hostile environment, where the formation process is still unknown.

Here we report on near and mid-infrared imaging observations of the dust envelope surrounding the star WR 112 (spectral class WC9). The morphology of this envelope provides clues to the nature of the stellar system, while the photometry

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allows us to estimate the properties of the dust and the total dust mass.

2. Observations

WR112 belongs to the group of 5 WC stars with the densest known dust envelopes (van der Hucht et al. 1996). We observed WR112 along with WR104 and WR118 with the University of Florida mid-IR imager "OSCIR" at the Gemini-North 8m telescope using the medium-band $7.9\mu\text{m}$, $12.5\mu\text{m}$ and $18.2\mu\text{m}$ filters on 7 May, 2001. For WR112 we supplemented the mid-IR data with near-IR narrow-band h and k images taken at the CFHT on 27 June 1999 with the adaptive optics bonnette and KIR camera, and broad-band L' images obtained at the IRTF on 28 May 2000 in the 'movie burst' (2×8192 0.01-sec exposures) mode of the NSFCAM imager. We also acquired images of point sources (PSF reference stars), usually immediately before and after the principal target, for image restoration. The original data cubes were split into individual frames, quickly checked and selected for image quality using basic image statistics for the OSCIR and CFHT data (initially compensated for atmospheric turbulence), or carefully selected using a specifically designed statistical procedure for the NSFCAM images (taken without compensation). The individual images were then appropriately shifted to form a final image for each wavelength/target/instrument. The final images were then restored using the images of the PSF reference stars and a maximum entropy algorithm (the 'stdas.analysis.restore.mem' task of IRAF⁴ for the CFHT data, enabling us to reach $\frac{1}{2}$ pixel ($0.018''$) resolution, or the 'stdas.analysis.restore.lucy' task of IRAF for the OSCIR and NSFCAM images, thus reaching 1-pixel resolution of $0.089''$ and $0.055''$, respectively).

3. Dust properties

While WR104 and WR118 show only modest extensions on scales of several $0.1''$, combination of the original mid-IR images of WR112 reveals three sets of regularly spaced arc-like structures extending out $3''$ from the central star (Fig. 1a).

It is apparent that the dust temperature gradually falls off outwards. The central source and two closest arcs form a W-like configuration, the middle part of which is also seen in the near-IR (Fig. 1b). The near-IR size of the central source, $\text{FWHM} = 0.089'' \pm 0.004''$, is consistent with earlier measurements (Ragland & Richichi 1998; Monnier et al. 2002): $\text{FWHM} = 0.059'' - 0.073''$. The near-IR SW elongation probably corresponds to the previously detected (Ragland & Richichi 1998) small-scale asymmetry in the dust envelope.

WR112 is the fourth case in which dust around a WR star has been mapped in some detail, with all the previous examples occurring in WC+O binaries (Marchenko, Moffat, & Grosdidier 1999; Monnier, Tuthill, & Danchi 1999; Tuthill, Monnier & Danchi 1999). Note that 6 other WR stars have been shown to possess an extended (presumably spherically-symmetric) envelope (Yudin et al. 2001; Monnier et al. 2002). WR112 is also known to be a variable non-thermal radio emission source (Chapman et al. 1999; Monnier et al. 2002), which might indicate binarity (Dougherty & Williams 2000). There are few viable scenarios for dust production in WR112. For example, the primordial circumstellar envelope would not have survived in the hard UV radiation-field of the WR progenitor. Periodic outbursts driven by stellar oscillations cannot explain the observed dust envelope-shape without invoking a factor of two azimuthal variation in the terminal-wind velocity along with an extreme latitudinal dependence of the mass-loss. Therefore, we assume that the dust is formed in the wind-wind collision zone of a massive binary system (thus resembling a collimated but rotating 'beam' for a distant observer) and expelled radially outward at a constant, terminal-wind velocity $v_\infty = 1200 \text{ km s}^{-1}$ (Rochowicz & Niedzielski 1995). We then calculate the resulting locus of maximum dust density and fit it to the observed dust distribution in the restored mid-IR images, taking the necessary orbital elements, P, e, i, ω, Ω as free parameters. We find a family of minimum- χ^2 solutions for counter-clockwise orbits, in which coupling of $e-i$ and $\omega-\Omega$ leads to some degree of degeneracy. Instead of relying solely on the single formal best fit, we therefore construct a synthetic solution by averaging all the possible combinations of solutions for which the χ^2 values lie within 5% of the absolute minimum. This average

⁴IRAF is distributed by the National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

solution has period $P = 24.8 \pm 1.5$ yr, eccentricity $e = 0.11 \pm 0.11$, orbital inclination $i = 38.0^\circ \pm 3.8^\circ$, periastron angle $\omega = 269.6^\circ \pm 18.5^\circ$ and orbital orientation $\Omega = 33.5^\circ \pm 7.9^\circ$ (1- σ errors). In Fig. 2 we plot the solution with the highest possible, but still plausible, eccentricity: $e = 0.40$. This particular model yields a dust locus that is actually very close to that derived from the synthetic solution. In general, the model provides fairly good fits to the SW arms, although it fails to explain the pronounced NE excursions, as well as the bright SW protuberance. The latter extends in the direction toward a stellar visual companion $\sim 1''$ from WR112 (Wallace, Moffat & Shara 2002, and our Fig.2), which is not seen at near-IR, and is therefore probably also invisible at mid-IR wavelengths. Clearly the dust-production rate depends on orbital phase, diminishing as expected around apastron but surprisingly also absent around periastron, contrary to the situation in the eccentric, long-period colliding-wind WR+O binaries WR137 and WR140 (van der Hucht, Williams, & Morris 2001; Marchenko, Moffat, & Grosdidier 1999). The average thickness, δr , of the dust arcs in the deconvolved images relative to the separation between the successive arcs, Δr (measured at the same orbital phase), gives an estimate of the shock-cone opening angle: $\Theta \sim 2\pi \times \delta r / \Delta r \sim 60^\circ - 110^\circ$, similar to that found in other colliding-wind WR+O systems (Marchenko et al. 1997; Bartzakos, Moffat, & Niemela 2001). In Table 1 we list the calculated orbital elements along with the main characteristics of the dust envelope and the assumed parameters.

To derive the basic dust properties, which fortunately do not depend sensitively on the adopted orbital parameters, we first deproject all apparent distances by applying the synthetic average orbit-solution. We calibrate the restored images using all available IR-flux measurements of WR112 (Williams, van der Hucht, & Thé 1987; van der Hucht et al. 1996), assuming that the system has not experienced any large-amplitude IR outbursts. In the mid-IR range, the relatively large apertures used in previous ground- and space-based observations will tend to smooth out the variability by averaging over the output of many dust-formation cycles. We deredden the near-IR data by applying a Galactic interstellar-extinction model (Arenou, Grenon, & Gomez 1992), then calculate the

net dust fluxes after subtracting the stellar component, approximated as $F_\lambda \sim \lambda^{-\alpha}$, with $\alpha = 2.97$ (Morris et al. 1993). Then we use the relation (Hildebrand 1983):

$$M_d(r) = \frac{4\rho F(\lambda, r)d^2a}{3B(\lambda, T(r))Q_e(\lambda, a)}, \quad (1)$$

where M_d is the dust mass, $F(\lambda, r)$ is the measured flux at a given position r , ρ is the grain density, $d=4.15$ kpc is the distance to WR112 (van der Hucht 2001), a is the grain size, $B(\lambda, T(r))$ is the black-body emissivity, and $Q_e(\lambda, a)$ is the grain emission coefficient. We adopt the general relation $Q_e(\lambda, a)/a = k\lambda^{-s}$ along with a $T = T_0 r^{-\beta}$ temperature profile (Williams, van der Hucht, & Thé 1987) and measure the fluxes $F(\lambda, r)$ over regions of fixed 7×7 pixel size ($0.623'' \times 0.623''$), assigning 15% /30% errors to $F(\lambda, r)$ in the inner/outermost arcs. Taking the ratios of fluxes at every given position in the envelope (except the very central part, where the spectral distribution cannot be represented by a single temperature) in order to reduce the number of free parameters and to be impervious to large positional fluctuations in $F(\lambda, r)$, we obtain via χ^2 -minimization the following estimates: $s = 0.90^{+0.22}_{-0.21}$, $T_0 = 320^{+12}_{-13}$ K, $\beta = 0.40^{+0.05}_{-0.05}$ (T_0 at $1''$; 95% confidence intervals). The dust emissivity index s , though loosely constrained, is close to the range expected for amorphous carbon in the near-mid-IR domain (Borghesi, Bussoletti, & Colangeli 1985; Suh 2000). On the other hand, the absence of the telltale $9.7\mu\text{m}$ silicate emission feature in the WR112 spectrum (van der Hucht et al. 1996) rules out the presence of any silicate-based mixture. The derived temperature profile follows the $\beta = 0.4$ dependence expected in the case of thermal equilibrium. Adopting $\rho = 2.0 \text{ g cm}^{-3}$ for the amorphous carbon dust, we estimate the dust mass separately for each 7×7 pixel² area of each of the 3 mid-IR images, then average the results (Fig. 3). We find a total $M_d = 5.5 \times 10^{28} \text{ g}$, integrated over the observed envelope. To compare our result with an earlier theoretical estimate of the mass we (a) account for the difference in the adopted distances to WR112 and (b) assume that the observed dust is created for 15 yrs (see Fig. 2) during each 25-yr orbital cycle, with 3 complete cycles accounted for. A model (Zubko 1998) with the assumption of a spherically-symmetric envelope gives $\dot{M}_d = 3.8 \times$

$10^{-7} M_{\odot} \text{yr}^{-1}$ (converted to $d=4.15$ kpc), while our estimate is $\dot{M}_d = 6.1 \times 10^{-7} M_{\odot} \text{yr}^{-1}$. Calculation of the *integrated* mass-ratios, $M(\text{innermost region+arcs}) : M(\text{middle arcs}) : M(\text{outer-most arcs}) = 1.0 : 0.6 : 0.2$, shows that the dust is gradually destroyed while leaving the system. Both the intense UV radiation field and sputtering caused by the high drift-velocities of the dust grains (Zubko 1998) may be responsible for the dust destruction. Nevertheless, the flattening of the trend at large radii in Fig. 3 suggests that some dust does reach the ISM.

Finally, we use eq. 1 to evaluate the characteristic size of the dust grains, by comparing via least-square minimization, the observed fluxes to the prediction of a simple model assuming that the envelope is populated by similar-sized spherical particles. We calculate the Mie absorption coefficients (Bohren & Huffman 1998), $Q_{abs}(\lambda, a) = Q_e(\lambda, a)$, using the optical constants for amorphous carbon (Zubko et al. 1996). As a second free parameter we take the integrated (innermost region+arcs) dust mass, allowing it to follow the general trend seen in Fig. 3. This gives an estimate of M_d within 25% of the previously calculated value, thus providing a good consistency check. We find a characteristic grain-size $a = 0.49^{+0.11}_{-0.11} \mu\text{m}$ (95% confidence interval), in line with the estimates obtained for WR112 from ISO spectroscopy, $a \sim 1 \mu\text{m}$ (Chair & Tielens 2001). The large grain size poses a serious problem for the theory of grain growth, which calls for $a \sim 0.01 \mu\text{m}$ (Zubko 1998).

4. Conclusions

The recently acquired high-resolution, high signal-to-noise near-mid-IR images of the WR star WR112 have enabled us to resolve and, for the first time, study in detail the extended dust envelope thought to be formed in the wind-wind collision zone of the long-period, $P \approx 25$ yr, binary. A simple approach involving a minimum of assumptions has allowed us to derive the basic dust properties: We find that the dust emissivity approximately follows the trend expected for amorphous carbon. The radial temperature-distribution shows the dust envelope to be in thermal equilibrium. The dust production-rate corresponds to $\sim 6\%$ of the total mass-loss rate, if for the latter we assume a typical value of $10^{-5} M_{\odot} \text{yr}^{-1}$. The characteris-

tic size of the dust particles, $a \sim 1 \mu\text{m}$, turns out to be much larger than expected from state-of-the-art models of dust growth. We also show that, despite the harsh conditions, $\sim 20\%$ of the newly formed dust can survive and escape the system, thus enriching the interstellar medium. This may have a direct implication for the process of heavy-element enrichment in the early Universe, when massive stars completely dominated the stellar scene.

We thank V. Zubko and P. Williams for helpful discussions, and J.-R. Roy and D. Toomey for assistance in observations. S.V.M., A.F.J.M. and R.D. gratefully acknowledge financial support from NSERC (Canada) and FCAR (Québec). This paper is based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: NSF (United States), PPARC (United Kingdom), NRC (Canada), CONICYT (Chile), ARC (Australia), CNPq (Brazil) and CONICET (Argentina). The observations were made with the mid-infrared camera OSCIR, developed by the University of Florida with support from NASA, and operated jointly by the Gemini Observatory and the University of Florida Infrared Astrophysics Group.

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Fig. 1.— a: False-color image of WR112 produced by log-scaling, normalizing and combining the 7.9, 12.5 and $18.2\mu m$ images as blue, green and red. The faintest details are $\sim 10^{-3}$ of the central source. The inset shows a point-spread-function standard at the same scale, used for image restoration. Fig. 1b: Zoom on the central source: combination of the maximum-entropy deconvolved, log-scaled and normalized images of WR112, with the narrow-band images h ($\lambda_0 = 1.64\mu m$, FWHM= $0.02\mu m$) and k ($\lambda_0 = 2.17\mu m$, FWHM= $0.02\mu m$) as blue and green, respectively, and the broadband L' image ($\lambda_0 = 3.75\mu m$) as red. The deconvolved and appropriately enlarged $7.9\mu m$ image is shown in contours. Small black stars mark the same central position on each image.

Fig. 2.— Deconvolved 18.2m image of WR112 with the overplotted model fit corresponding to the high-eccentricity case, $P = 23.5\text{yr}$, $e = 0.40$, $i = 35^\circ$, $\Omega = 40^\circ$, $\omega = 255^\circ$ (for the *average* derived parameters see Table 1), with the red line tracing the locus of visible dust, then gray line beyond. The grossly enlarged, projected orbit is shown in the lower left corner. The red dotted line points toward periastron. A small blue cross depicts the position of the visual companion.

Fig. 3.— The integrated (within 7×7 pixel areas) dust mass in grams. Filled triangles mark the central part of the image along with the two innermost arcs. Filled (open) squares/circles correspond to the SW (NE) middle/outer-most arc. The dotted line shows the trend expected in the case of mass conservation.

TABLE 1

ORBITAL PARAMETERS (‘SYNTHETIC SOLUTION’), BASIC DUST CHARACTERISTICS AND ASSUMED VALUES.

Parameter	Value	Errors ^a
P , yr	24.8	± 1.5
e	0.11	± 0.11
i	38.0°	$\pm 3.8^\circ$
ω	269.6°	$\pm 18.5^\circ$
Ω	33.5°	$\pm 7.9^\circ$
s	0.90	-0.21, +0.22
T_0 , ^b K	320	-13, +12
β	0.40	-0.05, +0.05
\dot{M}_d , g	5.5×10^{28}	—
\dot{M}_d , $M_\odot \text{ yr}^{-1}$	6.2×10^{-7}	—
a , μm	0.49	-0.11, +0.11
v_{dust} , km s^{-1}	1200	assumed
ρ_{dust} , g cm^{-3}	2.0	assumed
d , kpc	4.15	assumed

^aEither 1- σ or 95% confidence interval^b T_0 at $1''$